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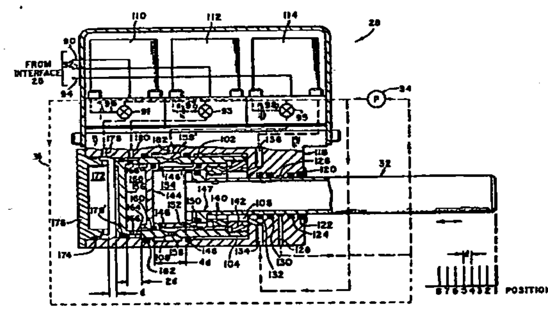
(54) **Multiple position digital actuator and method of digitally controlling a multiple position actuator element.**

(57) Multiple position digital actuator (28) particularly adapted to control a plurality of bleed air valves of a gas turbine engine by converting 2^n n-bit digital control words into 2^n physical positions of an actuator element (32), said actuator (28) comprising: n pilot solenoids (110, 112, 114) which are each associated with one of the bits of the digital control words and which respectively control n three-way valves (91, 93, 95), each having a first port in communication with a pressure source (34) and a second port in communication with the return side of said pressure source (34); and n telescoping piston-cylinder assemblies (32, 144, 156, 176), each defining an expansible chamber (154; 168; 172) which is in communication with the third port of a respective one of the three-way valves (91, 93, 95), each of the expansible chambers (154, 168, 172) being independently expanded or contracted to move the actuator element (32) under the control of an associated set of pilot solenoid and three-way valve according to the state of the bit applied to said pilot solenoid, and the distance moved by the actuator element (32) for adjacent piston-cylinder assemblies being in ascending powers of two (2^0d, 2^1d, 2^2d).



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Multiple position digital actuator and method of digitally controlling a multiple position actuator element

The invention relates to a multiple position digital actuator for converting 2^n n-bit digital control words into 2^n physical positions of an actuator element.

For the regulation of the operation of many apparatus today there is necessitated the physical positioning of a control member according to a schedule or control law. Usually, the mechanical positioning of the control member is accomplished by an actuation device responding through an interface to a control signal calculated by a controller. Increasingly, the control signal will be calculated by a controller including a digital electronic processor which will regulate the positioning of the actuator as a function of digital control words. Heretofore, the conversion of the information contained in the digital control words into physical positions has not been efficiently performed by conventional actuators.

Generally, either a digital-to-analog converter has been needed to control an analog actuator system positioning itself with respect to the analog signal or each bit of the digital control words has been used to control an associated binary actuator determining a separate position. The former method is quite complex and requires relatively expensive actuators or stepper motors while the latter method is power consuming and increases the weight of the whole system. Neither actuator technique is entirely satisfactory for the sophisticated digital control systems being developed for future utilization.

More specifically, the control of the operation of combustion engines based on their operating parameters may require many multipositional actuators. For example, to control a combustion engine of the gas turbine type an electronic controller has been used to control actuators for the bleed air valves of the compressor, the stator vane

positioning, the nozzle positioning, fuel control, and positioning of other control members. Additional control functions may be envisioned for multipositional actuators in the future.

With respect to a particular application for a multiposition actuator, the bleed air valves are a series of valves used to vent the compressor of a gas turbine engine when the air flow between adjacent stages is mismatched to prevent the compressor from stalling. These valves are used primarily for starting or other operational sequences where one or more of the series is opened to regulate the quantity of air being supplied to the final compressor stages. The air bleed valves have also been used to provide a supply of pressurized air to other areas of the engine system.

Previously, each air bleed valve has been controlled by an individual solenoid. These solenoids were controlled by digital words where one bit was assigned to each valve. The presence of a bit 1 in the control word would actuate a particular air bleed and the absence of a bit 1 would close it. However, this system mandates that each solenoid will be large or mechanically powerful enough to perform the task assigned. Since the solenoid valves work against compressor pressure they have been by necessity relatively heavy. The excess weight of these valves in gas turbine engine systems for aircraft is viewed critically.

Moreover, the use of these large solenoids requires that a separate driver circuit be used for each one. The logic levels developed digitally have to be transformed into power levels sufficiently to drive the large solenoids. These drivers consume considerable amounts of power which must be generated onboard in aircraft. The increased weight for aircraft of the electric generation devices used to create this excess power is also undesirable.

The present invention overcomes the limitations and disadvantages of the prior art arrangements by providing a multiple position digital actuator for converting 2^n n-bit digital control words into 2^n physical positions of an actuator element, comprising: n piston-cylinder combinations, each of said combinations being operable to move the actuator element independently of the other combinations through a

respective distance controlled by an expansible chamber disposed between the piston and cylinder of each of said combinations, each of the distances being related to the other distances by powers of two; and n pilot solenoids, each being associated with an expansible chamber and operable to control means for communicating pressure from a pressure source to a corresponding chamber or from said corresponding chamber to the pressure return side of the pressure source thereby causing expansion or contraction of the chamber and movement of the actuator element, and each of the pilot solenoids being associated with one of the bits of the digital control words and actuated by one of the states of said one bit.

A number of distinct advantages are obtained from an actuator constructed in this manner. In aircraft applications one important advantage is weight savings when used in an air-bleed control system. The individual large solenoids of the previous systems are replaced by much lighter pilot valves.

Additionally, the driver circuits which were used to transform logic level signals into control level signals can be eliminated or drastically reduced. The pilot solenoids consume much less power and if judiciously chosen can be run directly from the output ports of a microprocessor or logic circuitry. This feature represents not only a circuitry savings but an electrical power capacity reduction for an aircraft electrical generator system which translates directly into a weight savings.

The weight savings can be considerable because the invention takes advantage of the mechanical force amplification available by controlling a pressure source with the piston-cylinder combinations. This amplification can be obtained readily without sacrifice in particular applications because many engines already include fluid power sources having excess capacities. Thus, the actuator can use small pilot solenoids to produce large mechanical forces. In aircraft or other applications using a gas turbine engine the compressor airflow or a starter motor airflow can be utilized for this function.

One way of carrying out the invention is described in detail below with reference to the drawings which illustrate

one embodiment of the invention, in which:

FIGURE 1 is a schematic block diagram illustrating an air bleed control system for a gas turbine engine utilizing a multiple position digital actuator constructed in accordance with the invention;

FIGURE 2 is a partially cross-sectional side view of the actuator used in the system illustrated in FIGURE 1; and

FIGURE 3 is an actuation table illustrative of the translation of digital control words into physical positions of the actuator.

With reference now to FIGURE 1, there is shown an air bleed control system for a turbo-jet engine utilizing a multiple position digital actuator constructed in accordance with the invention. The turbo-jet engine generally designated as 10 includes an air inlet 12, a low pressure compressor section 14, a high pressure compressor section 15, a burner section 16, a turbine section 18, an exhaust nozzle 20, and an afterburner 22. Air drawn through the inlet 12 is compressed by the two compressor sections 14 and 15 and when fuel is injected into the burner section 16, a highly energetic burning gas is exhausted through nozzle 20 to be reburned in afterburner 22. As is known, the reaction of the engine to the exhaust gas is a forward thrust used for motive power. The turbine section 18 drives the compressor sections 14,15 by consuming a portion of the exhaust gas energy before it exits the nozzle 20. Inasmuch as this invention is not primarily concerned with the reaction engine, and its parts are conventional, it will not be more fully described.

Between the stages of the high pressure compressor section 15 is located a plurality of air bleed valves in an assembly 30. These valves are used to vent the pressurized air from the stages of the low pressure compressor section 14 before it is input to the stages of the high pressure compressor section 15. It is known that these may be used for starting, other bleed sequences, or for powering other auxiliary devices in an aircraft. Such other auxiliary devices include anti-icing mechanisms or boundary layer controls.

The assembly 30 for the actuation of the air bleed

valves comprises a tubular actuator piston or element 32 from a multiple position digital actuator 28. The actuator 28 is connected to an electronic controller 24 through an interface circuit 26. The interface circuit 26, for example, if the controller 24 is a microprocessor, would preferably be the microprocessor output ports.

The controller 24 if scheduling a starting sequence will have as an input the speed signal $N\ell$ from the low pressure compressor section 14 and the speed signal Nh from the high pressure compressor section 15. Noting the differences between these two input signals will allow the controller to schedule an output to the interface circuit 26 in the form of a three-bit digital word. It is readily apparent that other inputs may be provided to the controller 24 for scheduling the auxiliary devices or for different sequencing during startup or other control. Other engine parameters that may be useful in air bleed control are temperatures and pressures of the turbine and compressor sections.

Power for the multiple position digital actuator 28 is obtained from a pressure source 34 which can alternatively be supplied from a tap of the compressor sections of the engine or from a pressure source such as an air starter motor or the like. Other sources of fluid pressure that are readily available may also be used. Pressure sources found in a gas turbine engine system include high pressure fuel and hydraulic pumps or the like.

The actuator 28 receives the digital word and converts it directly into a position of the actuator piston 32 by a piston-cylinder assembly which will be more fully described hereinafter. The number of positions of the actuator piston 32 is related to the number of digital control words. In the present example, the digital control words have three bits and, therefore, the actuator piston 32 will have eight discrete physical positions.

The actuator 28 will now be more fully explained with reference to FIGURE 2. The actuator 28 comprises three pilot solenoids 110, 112 and 114, respectively, which are adapted to receive the digital input signal or control word and position the actuator piston 32 with respect to the

value of that input signal. There are three solenoids present, each associated with one bit of the digital control word, and there are 2^n or eight positions available for the actuator piston 32. Assuming one position will be taken to signify that all the air bleed valves are closed, there will then be seven positions remaining, one to correspond to the opening of each air bleed valve or the extent of opening of the valve.

The coils of the solenoids 110, 112, and 114 are connected via signal lines 90, 92, and 94, respectively, to the controller 24 through interface 26. A high voltage level on a signal line, representing that a bit 1 is present in the digital control word for that bit position, will energize the coil and actuate a three-way valve of the solenoid. The solenoids, for example, solenoid 110, upon energization will vent a pressure port 178 via vent 96 through a valve 91. Upon deenergization the pressure port 178 will be connected through the valve 91 to pressure source 34. Similarly, solenoids 112, 114, actuate valves 93 and 95, respectively, to connect pressure ports 180, 182, to vents 97, 98. When deactivated the valves 93, 95 will communicate pressure ports 180, 182 to the pressure source 34. The vents 96, 97, 98 are connected to return fluid back to the pressure source 34 through a return conduit 36.

Therefore, a high voltage level in a bit position for a corresponding solenoid will vent a pressure port and a low voltage level will pressurize it. This method will transform the digital electrical signal at signal lines 90, 92, and 94 into a fluidic pressure signal of a binary nature at the ports 178, 180, and 182. The fluidic signal is subsequenly further transformed into mechanical actuation motion by a piston-cylinder assembly to linearly move actuator piston 32 through its eight positions.

Each of the solenoids 110, 112, and 114 is preferably a conventional low power solenoid that can be energized without a large power consumption or complex driving circuitry. Advantageously, the solenoids can be operated directly from the digital gate levels of the controller 24 such as those found on the output ports of a microprocessor or the

like. Normally, these gate levels are between 5 volts and 15 volts for a digital control system.

The pressure source 34 in combination with the piston-cylinder assembly then provides the needed force amplification for the movement of the actuator piston 32 against the pressure of the compressor. As the actuator is depicted in FIGURE 2, the actuator piston 32 is at its furtherest rightward limit and will move in seven more equal increments of distance d to the left upon actuation by the digital control word. An actuation table, labeled FIGURE 3, describes the correspondence between the values of the digital control words and the actuator piston positions.

The actuator piston 32 is essentially an elongated actuation element of a hollow tubular shape connected integrally to a piston-shaped flange 147 at its actuation end. The piston extends through an aperture formed in a base 118 of the actuator 28. The piston 32 is sealed hydraulically by dual rings 130 and 132 of suitable material compressed between the actuation piston and a set of grooves cut in the aperture of the base 118. Even with these dual rings a weep ring 126 has been cut in the aperture to drain the fluid pressure which escapes. The weep ring 126 communicates to a weep port 128 which returns the escaped fluid to low pressure return of the pressure source 34 via a suitable conduit.

Another ring 124 of lesser sealing capability is compressed between the actuator piston 32 and a groove cut in the aperture to provide a final seal for the actuator piston 32. To lubricate the actuation piston 32 an oil-impregnated packing material 122 is provided in a step cut in the aperture of the base 118. Packing material 122 is retained in the step by a face washer 120 that fits against the base 118.

The flange 147 of the actuator piston 32 is telescoped into a generally cylindrically shaped first cylinder 144. The first cylinder is closed at one end and open at the other. The first cylinder 144 retains the flange 147 of the actuator piston 32 by the means of a centrally bored first annular nut 140 being screwed onto a threaded portion at its open end. The actuator piston 32 extends through the center bore of the first nut 140 and is free to move reciprocally depending on

the movement of the flange 147. Fluid pressure communication is prevented between the open end of the first cylinder 144 and the closed end thereof by a ring 150 compressed in a groove cut circumferentially around the flange 147. The flange 147 is operable to move between the closed end of the first cylinder 144 and a position where it is stopped by abutment against the first nut 140.

The first cylinder 144 and actuator piston 32 form a first piston-cylinder assembly which is telescoped into another generally cylindrical second cylinder 156. As is the first cylinder 144, the second cylinder 156 is closed at one end and open at the other. The second cylinder 156 retains the first piston-cylinder assembly by a centrally bored second annular nut 142 screwed onto a threaded portion at the open end thereof. The actuator piston 32 additionally extends through the center bore of the second nut 142 and is free to move reciprocally depending upon the movement of the first piston-cylinder assembly. Fluid pressure communication is prevented between the open end of the second cylinder 156 and the closed end thereof by a set of rings 152, 160 compressed in grooves cut circumferentially around the first cylinder 144. A first auxiliary chamber 102 is defined by notch machined around the outside wall of the first cylinder 144 and the inside wall of the second cylinder 156. The first auxiliary chamber 102 is also isolated from fluid communication by rings 152, 160. The first piston-cylinder assembly is operable to move between the closed end of the second cylinder 156 and a position where it is stopped by abutment against the second nut 142.

The assembly of the first piston-cylinder assembly and the second cylinder 156, forming a second piston-cylinder assembly, is mounted within a generally cylindrical base cavity 104 in the base 118. The base cavity 104 is open at one end and closed at the other end. The cavity is sealed at its open end by an end cap 176 and a ring 174 compressed in a groove cut circumferentially therein. The actuator piston 32 is free to move reciprocally with respect to the base cavity 104 depending upon the movement of the second piston-cylinder assembly. Three rings 148, 162, and 178' block fluid communication between the closed end and open end of the base cavity

104. In addition, the ring set 148, 162 prevent fluid communication to and from a second auxiliary chamber 108 formed from a notch machined around the inside wall of the base cavity 104 and the outside wall of the second cylinder 156. Still further, the ring set 162, 178' prevents fluid communication to and from a third auxiliary chamber 164 defined by a groove cut in the outside wall of the second cylinder 156. The second piston-cylinder assembly is operable to move between the closed end of the base cavity 104 and a position where it is stopped by abutment against the end cap 176.

The telescoping assembly of pistons and cylinders described, separates the base cavity 104 into a number of expansible and contractable pressure chambers. A variable volume pressure chamber 154 is defined by the inner wall of the first cylinder 144 and the flange 147 of the actuator piston 32. Another variable volume pressure chamber 168 is defined between the inside wall of the second cylinder 156 and the closed end of the first cylinder 144. A third variable volume chamber 172 is defined by the end cap 176 and the closed end of the second cylinder 156. Each of the variable volume pressure chambers may have its volume changed by reciprocation of the respective telescoping elements defining its boundaries. Specifically: actuator piston 32 reciprocates in the first cylinder 144 to change the volume of chamber 154; the first piston-cylinder assembly 144, 32 reciprocates in the second cylinder 156 to change the volume of the pressure chamber 168; and the second piston-cylinder assembly 144, 32, 156 reciprocates in the base cavity 104 to change the volume of the pressure chamber 172.

Each variable volume chamber is associated with an individual pressure port. Specifically, pressure port 178 communicates directly with chamber 172 while pressure ports 180 and 182 communicates through the auxiliary pressure chambers to chambers 168 and 154, respectively. Pressure port 180 communicates initially to the third auxiliary chamber 164 and then to chamber 168 via vents 166, 166'. Similarly, pressure port 182 communicates via the first and second auxiliary chambers 102, 108 to chamber 154. Initially, pressure port 182 communicates with the second auxiliary chamber 108 and

it with the first auxiliary chamber 102 through fluidic connection by apertures 158, 158'. The first auxiliary chamber 102 then communicates with chamber 154 via vents 146, 146'. Accordingly, it may be said that each of the pressure ports 178, 180, 182 communicates with an associated one of the expansible chambers 154, 168, 172 by a number of auxiliary chambers 102, 108, 164, if any, which number is dictated by the power of two represented by the ordinal number of the expansible chamber minus one. For example: for the 1st expansible chamber 172, the power of two is $2^{1-1}= 2^0$, thus there are no auxiliary chambers; for the 2nd expansible chamber 168, the power of two is $2^{2-1}=2^1$, thus there is one auxiliary chamber 164; and for the 3rd expansible chamber 154, the power of two is $2^{3-1}=2^2$, thus there are two auxiliary chambers 102, 108.

Consequently, the pressure chambers are, because of their association with individual pressure ports, each associated with an individual signal line and, therefore, an individual bit of the incoming signal. A high level on a signal line, indicating the presence of a bit 1, will vent the respective chamber and a low level on the signal line, indicating the absence of a bit 1, will pressurize the chamber.

Pressure ports 134 and 136 are provided to supply a bias chamber 106 with fluid pressure from the pressure source 34. The bias chamber 106 is formed by that part of the base cavity 104 between ring 148 and the closed end of the base cavity 104. Pressure in this chamber causes movement of the piston-cylinder assemblies when the expansible chambers 154, 168, and 172 are vented. Movement by the piston-cylinder assemblies in the other direction is caused by the force unbalance because of the differing areas over which the pressure source operates.

In operation, the actuator piston 32 moves to positions 1 through 8 by venting or pressurizing combinations of the chambers 154, 168, 172, according to presence or absence of bits 1 in the digital control word. Energizing solenoid 110 causes the second cylinder 156 to move a distance <u>d</u> and thereby move the actuator piston 32 an identical

distance. Energizing solenoid 112 causes the first cylinder 144 to move a distance 2d and thereby move the actuator piston 32 an identical distance. Finally, energizing solenoid 114 causes the actuator piston 32 to move a distance of 4d. Thus, the movement of the actuator piston 32 caused by individual solenoids is independent of the others but related to its bit position by a power of two. It is evident that combinations of these movements will then produce movements corresponding to the actuation table shown in FIGURE 3.

While the preferred embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that various modifications and changes may be made thereto. For example, the pressure source 34 has been described as an air pressure source. It would be obvious to provide any other type of fluid pressure source, vacuum or above ambient, to power the piston-cylinder assemblies. It is recognized that what is necessitated by the invention is a difference in pressures between the chambers to operate the actuator piston. As a consequence, the actuator piston may be operated in the sequence described hereinbefore where it moves from right to left as combinations of chambers are vented or it could just as easily move from left to right by pressurizing combinations of chambers. It is also well within the ordinary skill of the art to expand or reduce the invention to any force or size desired. An expansion or reduction of the invention may also be consummated with respect to the size of the digital control words and number of actuation positions. Additional piston-cylinder assemblies and pilot solenoids can be added to adapt the invention to any size of digital control words.

Claims:

1. A multiple position digital actuator (28) for converting 2^n n-bit digital control words into 2^n physical positions of an actuator element (32), characterized in that it comprises: n piston-cylinder combinations (32,144,156,176), each of said combinations (32-176) being operable to move said actuator element (32) independently of the other combinations through a respective distance controlled by an expansible chamber (154; 168; 172) disposed between the piston and cylinder of each of said combinations (32-176), each of the distances (d,2d,4d) being related to the other distances by powers of two; and n pilot solenoids (110,112,114), each being associated with an expansible chamber (154;168;172) and operable to control means (91;93;95) for communicating pressure from a pressure source (34) to a corresponding chamber or from said corresponding chamber to the pressure return side of said pressure source (34) thereby causing expansion or contraction of the chamber and movement of said actuator element (32), and each of said pilot solenoids (110,112,114) being associated with one of the bits of said digital control words and actuated by one of the states of said one bit.

2. A multiple position digital actuator as claimed in Claim 1, characterized in that said n piston-cylinder combinations (32-76) are telescoped within each other such that the distance moved by the actuator element (32) for adjacent combinations is in ascending powers of two ($2^0d,2^1d,2^2d$).

3. A multiple position digital actuator as claimed in Claim 1, characterized in that said n piston-cylinder combinations (32-76) are telescoped within each other such that the distance moved by the actuator element (32) for adjacent combinations is in descending powers of two ($2^2d,2^1d,2^0d$).

4. A multiple position digital actuator as claimed in Claim 1, characterized in that said actuator element (32) comprises an elongated body with a flange (147) on one end, said flange (147) acting as a piston and being disposed within a first cylinder (144) of the n piston-cylinder combinations (32-76).

5. A multiple position digital actuator as claimed in Claim 4, characterized in that there is provided means (34,106) for generating a force opposing movement of said actuator element (32) in one direction.

6. A multiple position digital actuator as claimed in Claim 5, characterized in that there are provided n pressure ports (178,180,182), each associated with and controlled by one of said n pilot solenoids (110,112,114), for pressurizing said expansible chambers (154,168,172).

7. A multiple position digital actuator as claimed in Claim 6, characterized in that each of said pressure ports (178,180,182) communicates with an associated one of said expansible chambers (154,168,172) by a number of auxiliary chambers (164;102,108), if any, which number is dictated by the power of two represented by the ordinal number of the expansible chamber minus one.

8. A multiple position digital actuator as claimed in Claim 1, characterized in that said pressure source (34) is a compressed air source.

9. A multiple position digital actuator as claimed in Claim 1, characterized in that said pressure source (34) is a vacuum air source.

10. A method of digitally controlling a multiple position actuator element (32), characterized in that it comprises the steps of: generating 2^n n-bit digital electrical signals representative of the 2^n physical positions of the actuator element (32); converting the individual n-bit electrical signals into corresponding individual n-bit fluidic signals; and converting said individual n-bit fluidic signals by means of n piston-cylinder assemblies (32,144, 156,176) into individual position signals acting upon the actuator element (32) to cause it to be moved to the 2^n physical positions corresponding to the 2^n n-bit digital electrical signals.

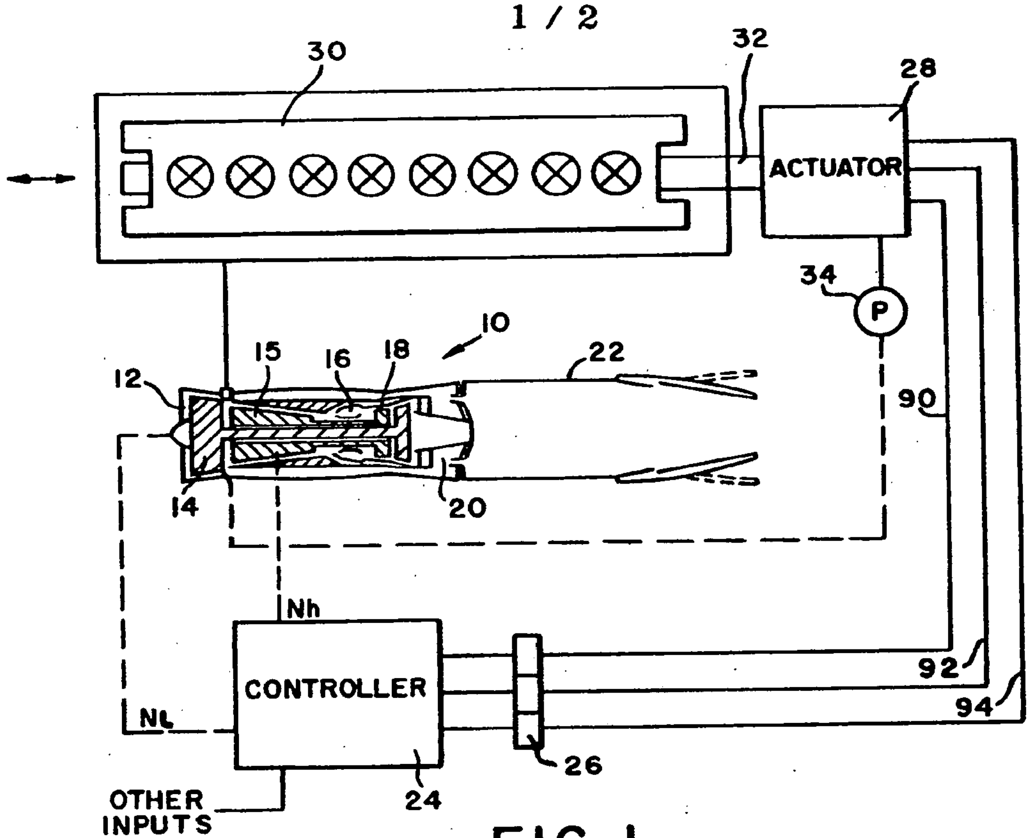
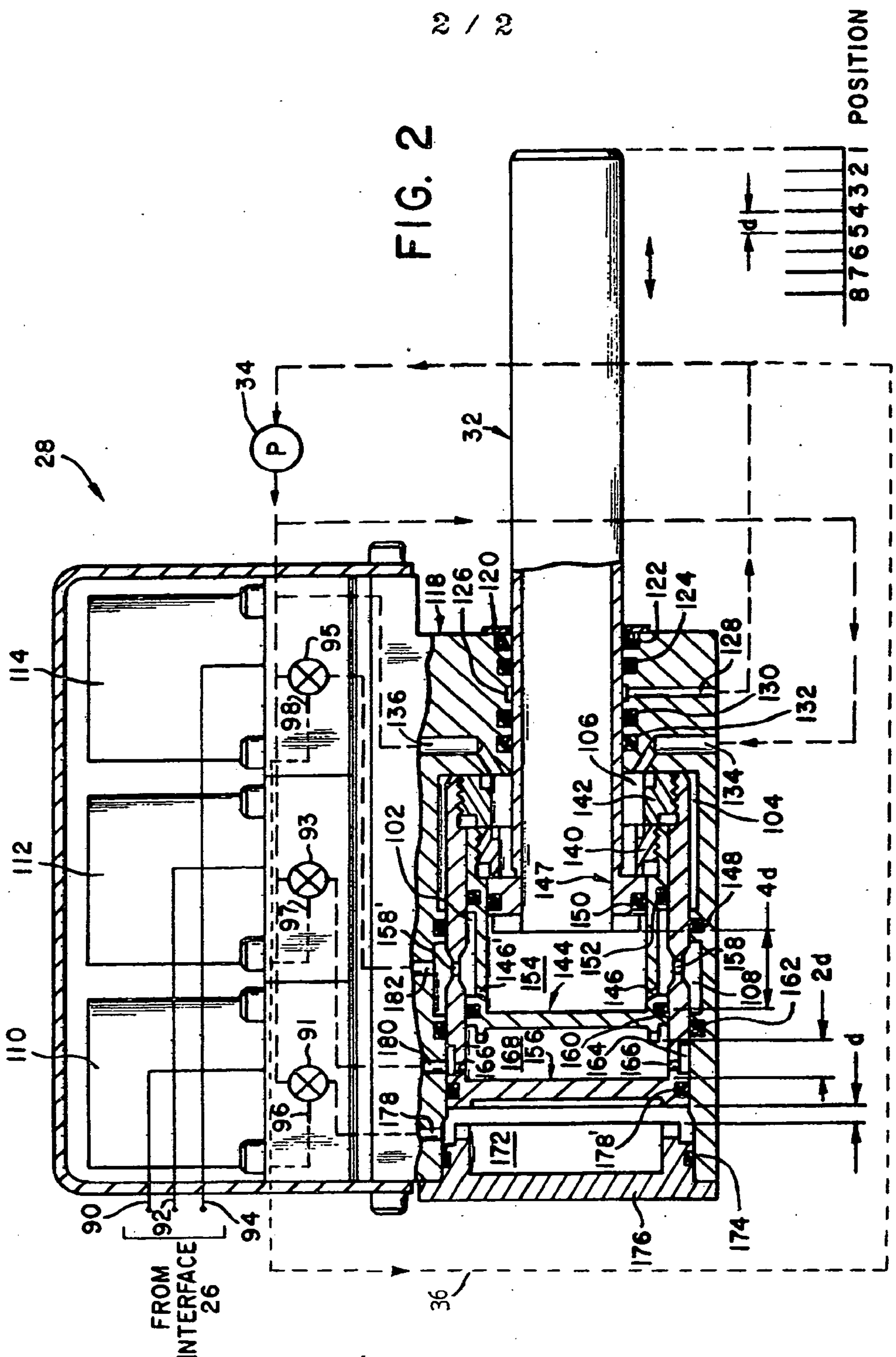


FIG. 1

ACTUATION TABLE

SOLENOID 114	SOLENOID 112	SOLENOID 110	POSITION
0	0	0	1
0	0	1	2
0	1	0	3
0	1	1	4
1	0	0	5
1	0	1	6
1	1	0	7
1	1	1	8

FIG. 3



POSITION
8 7 6 5 4 3 2 1
d
28
34
P
32
36
110
112
114
90
92
94
FROM INTERFACE 26
91
93
95
96
97
98
102
104
106
108
118
120
122
124
126
128
130
132
134
136
140
142
144
146
146'
147
148
150
152
154
156
158
158'
160
162
164
166
166'
168
172
174
176
178
178'
180
182
4d
2d
d

FIG. 2

0045228

European Patent Office

EUROPEAN SEARCH REPORT

Application number
EP 81 40 1073

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim
X	CH - A - 407 759 (SCHWEIZERISCHE LOKOMOTIV- UND MASCHINENFABRIK) * Entire document * --	1-8,10
X	GB - A - 1 007 633 (SPERRY GYROSCOPE) * Entire document * --	1-7
X	US - A - 3 114 296 (SMITH) * Entire document * ----	1-7

CLASSIFICATION OF THE APPLICATION (Int. Cl.³)

F 15 B 11/12

TECHNICAL FIELDS SEARCHED (Int. Cl.³)

F 15 B

CATEGORY OF CITED DOCUMENTS

X: particularly relevant
A: technological background
O: non-written disclosure
P: intermediate document
T: theory or principle underlying the invention
E: conflicting application
D: document cited in the application
L: citation for other reasons

&: member of the same patent family, corresponding document

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	14-10-1981	KNOPS

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